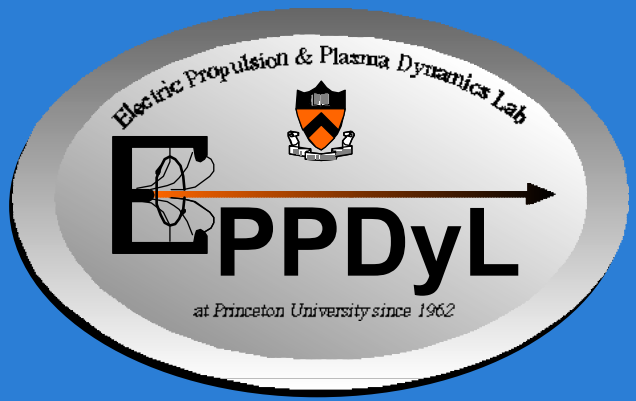
Advanced Electrodeless Plasma Propulsion Concepts



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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
25 JUN 2004	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Advanced Electrodeless Plasma Propulsion Concepts	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Electric Propulsion & Plasma Dynamics Lab Princeton University**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001793, International Symposium on Energy Conversion Fundamentals Held in Istanbul, Turkey on 21-25 June 2005., The original document contains color images.

14. ABSTRACT

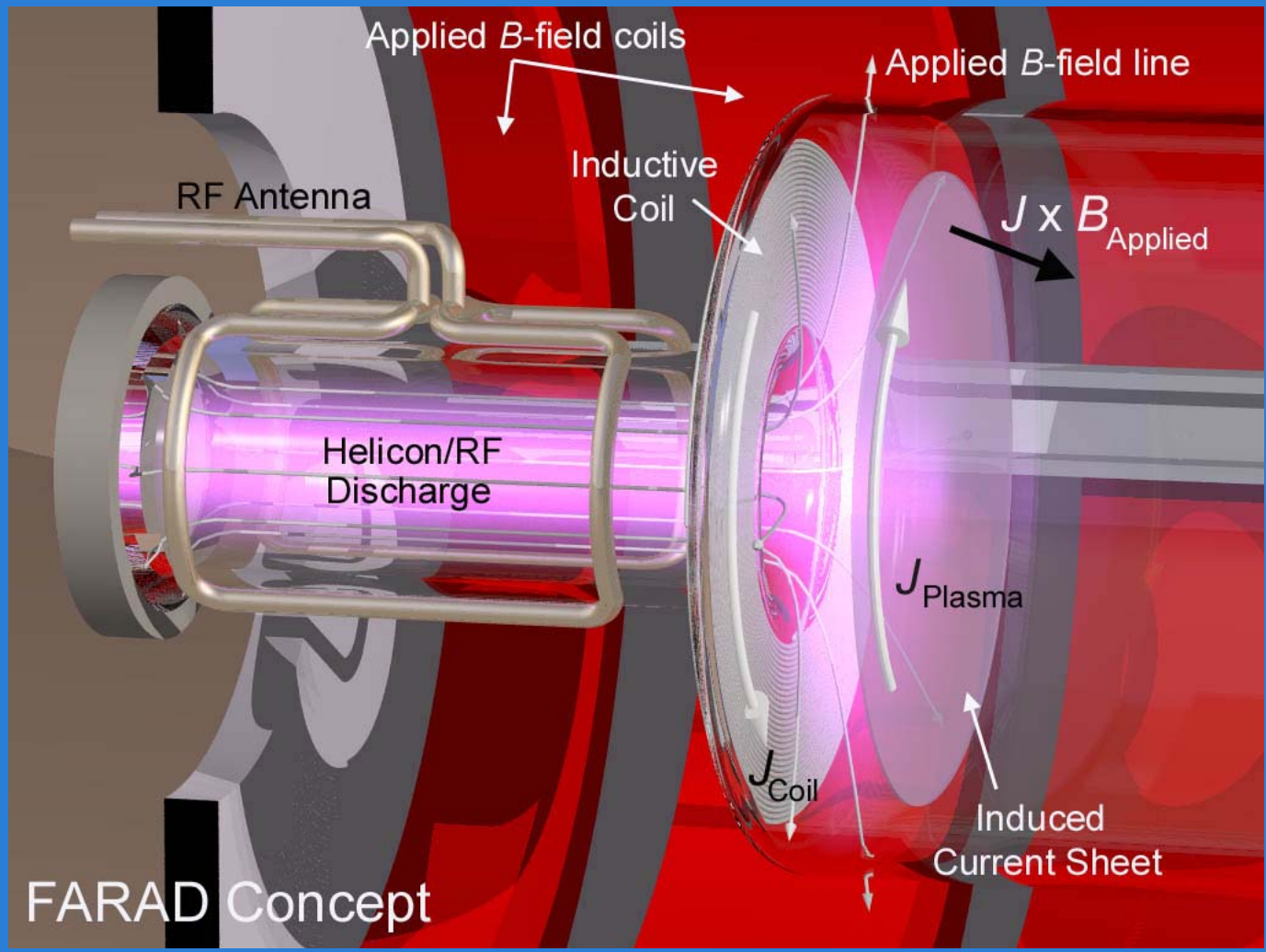
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**35**	

Outline

- I. FARAD: Faraday Accelerator with RF-Assisted Discharge
  - Basic Concept
  - Advantages
  - Basic Questions and Approach
  - Results of Proof-of-concept Experiment
- II. Ion Acceleration by Beating Electrostatic Waves
  - Basic Concept
  - Advantages
  - Basic Challenges
  - Status of Research

FARAD: Faraday Accelerator with RF-Assisted Discharge



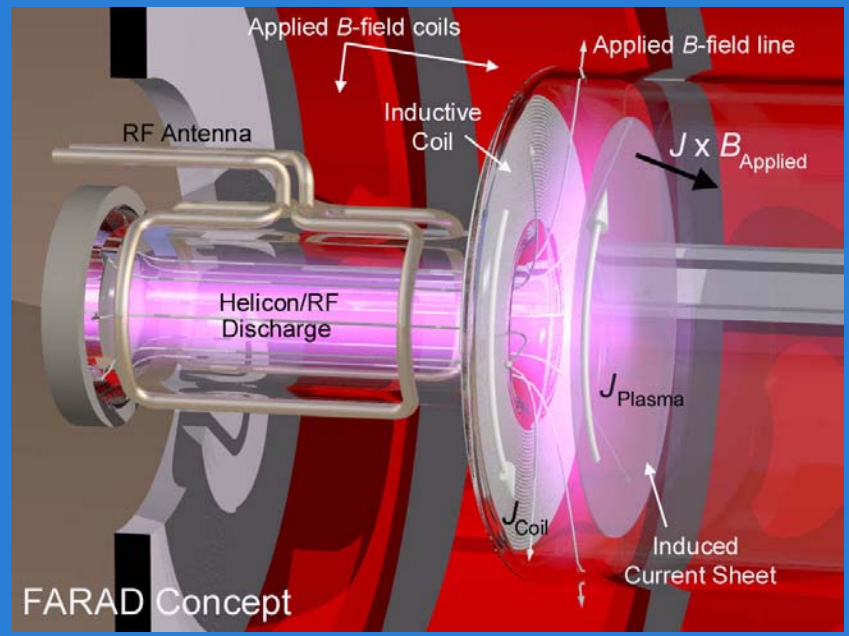
FARAD: Advantages

General:

- Completely electrodeless
- EM acceleration: High thrust density & I_{sp}
- Compatibility with a wide variety of propellants
- High mass utilization efficiency
- Accelerating forces are *always* perpendicular to ***B:*** No detachment issues
- Pulsed: can be used on power-limited s/c

With respect to PIT:

- Much more compact device
- No obstacles in plasma stream
- Additional axial Lorentz force: $J_\theta B_r$
- Plasma confinment through $J_\theta B_z$ leads to low wall losses



FARAD: Basic Questions

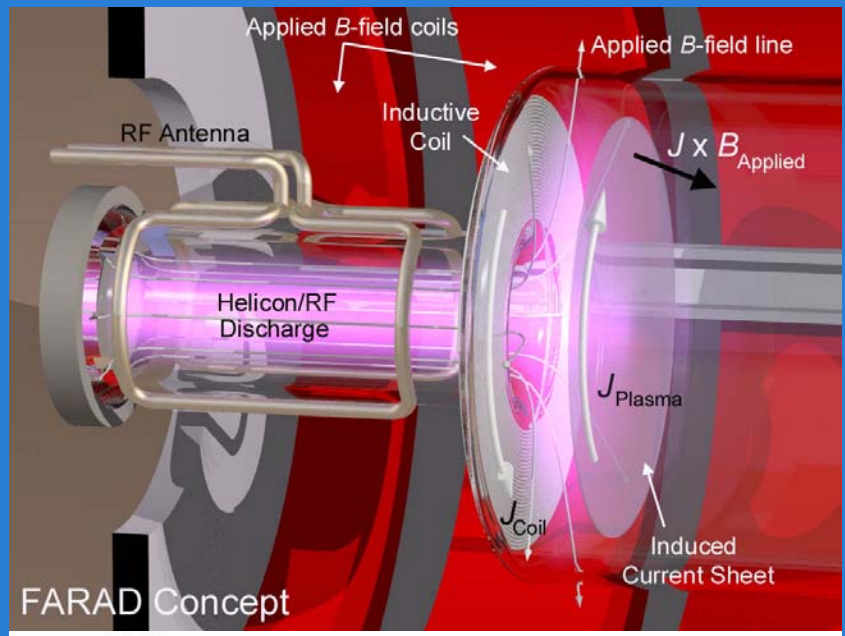
- What are the fundamental features and governing relations of the acceleration mechanisms?
- What are the fundamental limitations and major loss mechanisms?
- What are the scaling laws?
- How to choose the various controllable parameters (propellant, injected mass bit, RF power, B-field strength and topology, RF pulse length, inductive coil current and pulse length, geometrical dimensions, etc.) in order to optimize the performance?

FARAD: Approach

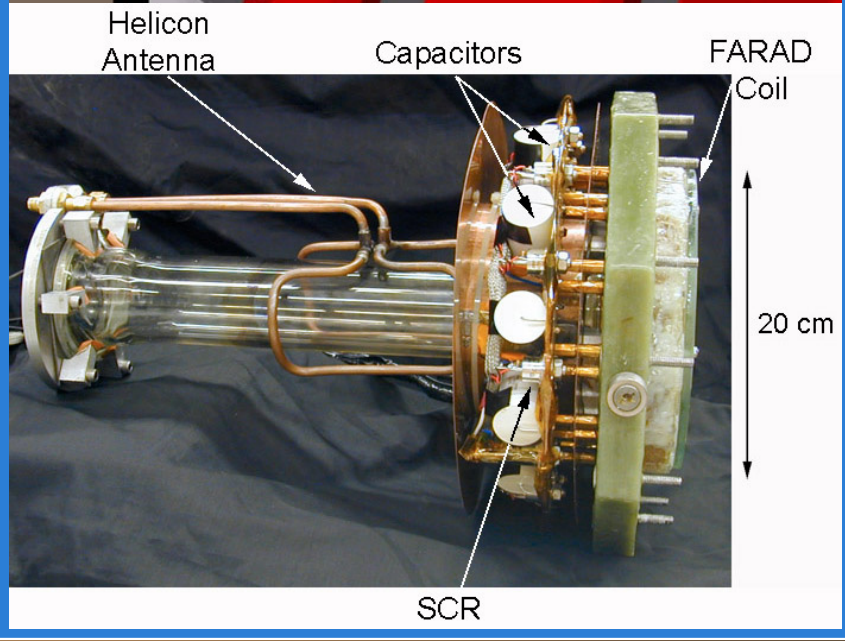
- ✓ Develop **Proof-of-concept Experiment** and demonstrate current sheet formation and acceleration.
- Extensive Characterization of Plasma, Current Sheet and accel. mechanisms
- Analytical and Numerical Modeling
- Optimization of Operational Parameters
- Design and Manufacturing a Prototype FARAD Thruster
- Extensive Performance Testing and Optimization

FARAD: Proof-of-Concept Experiment

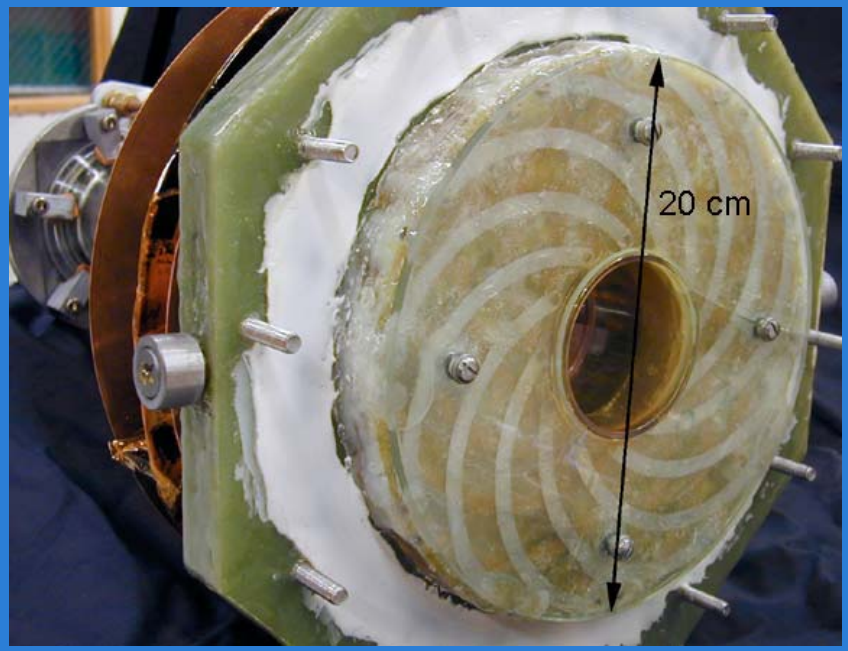
Concept

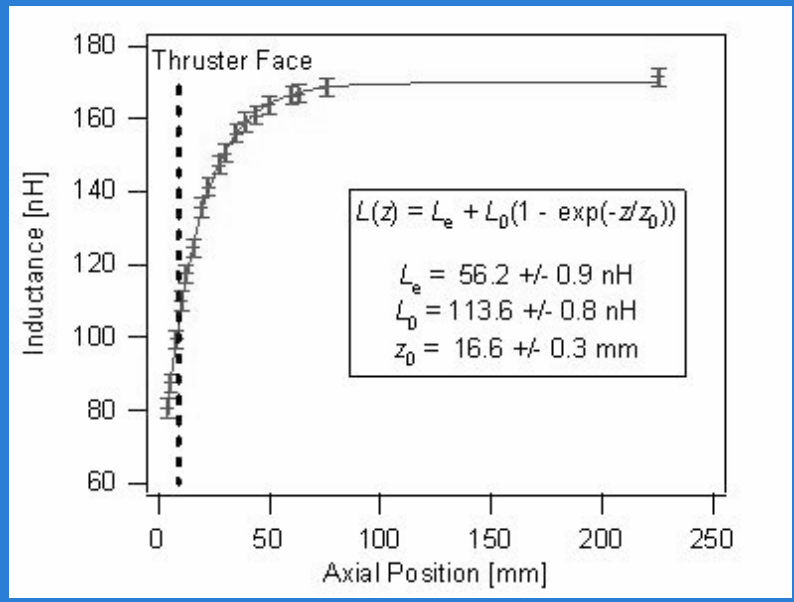


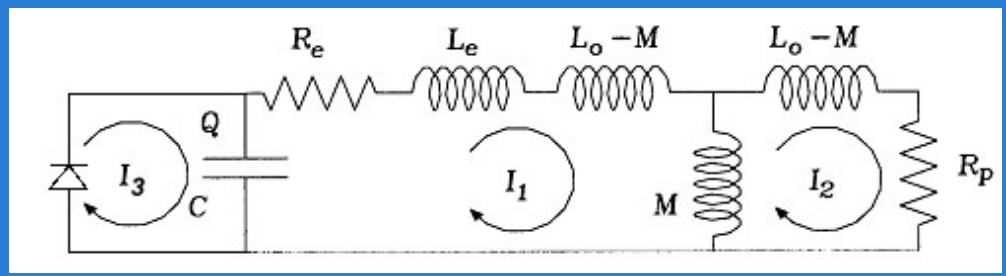
Experiment



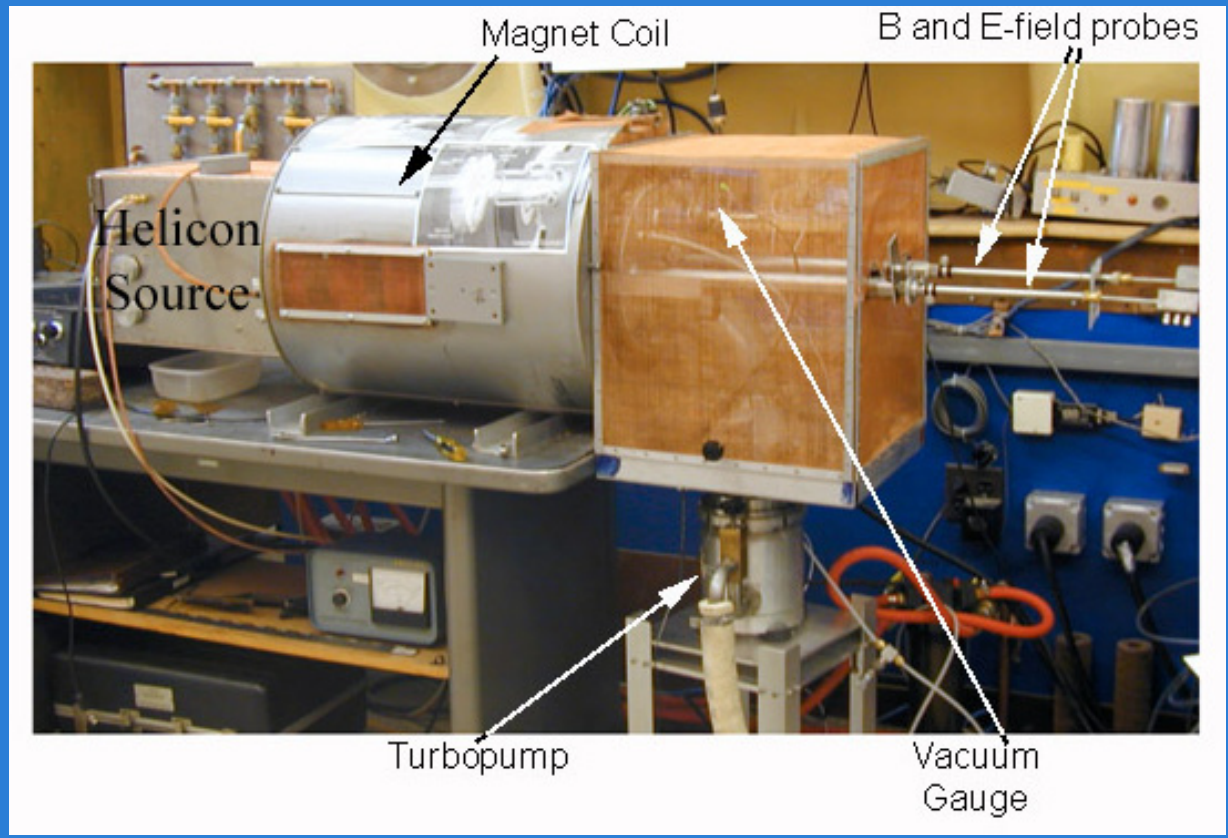
FARAD: Proof-of-Concept Experiment: J_θ coil



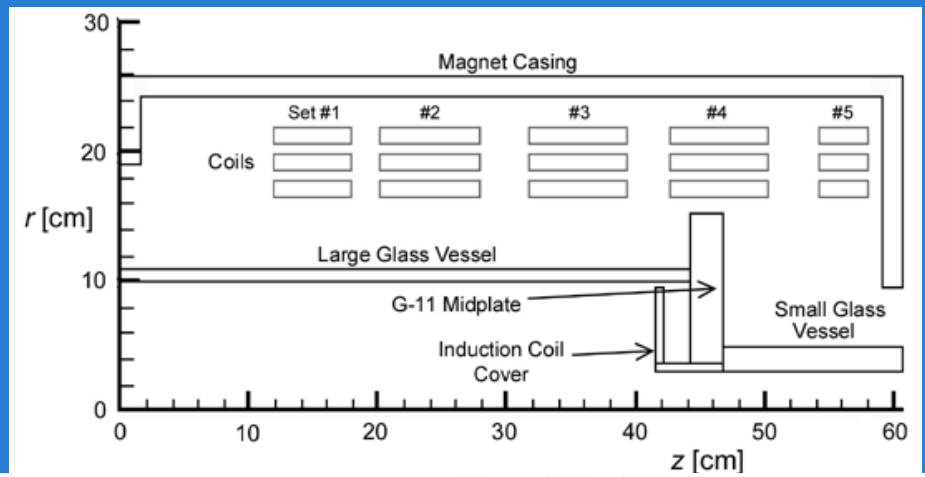


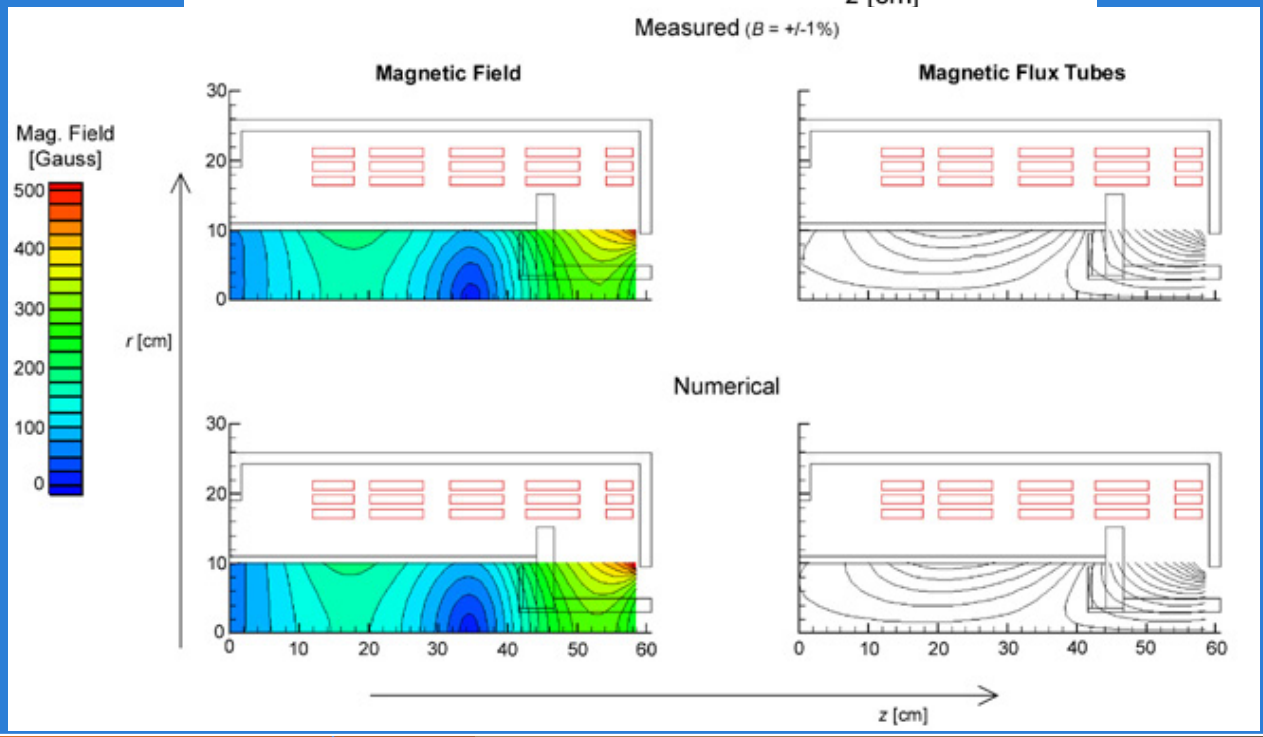


FARAD: Proof-of-Concept Experiment: Set-up

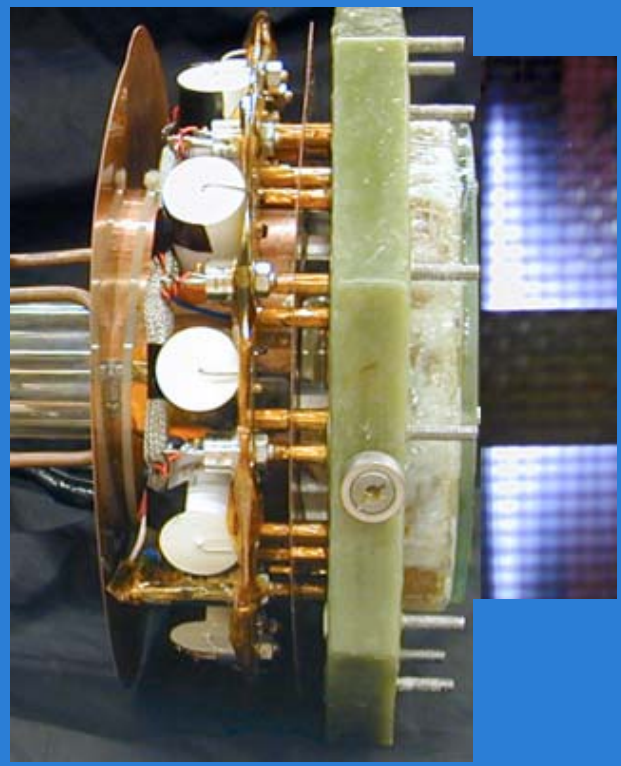


Field

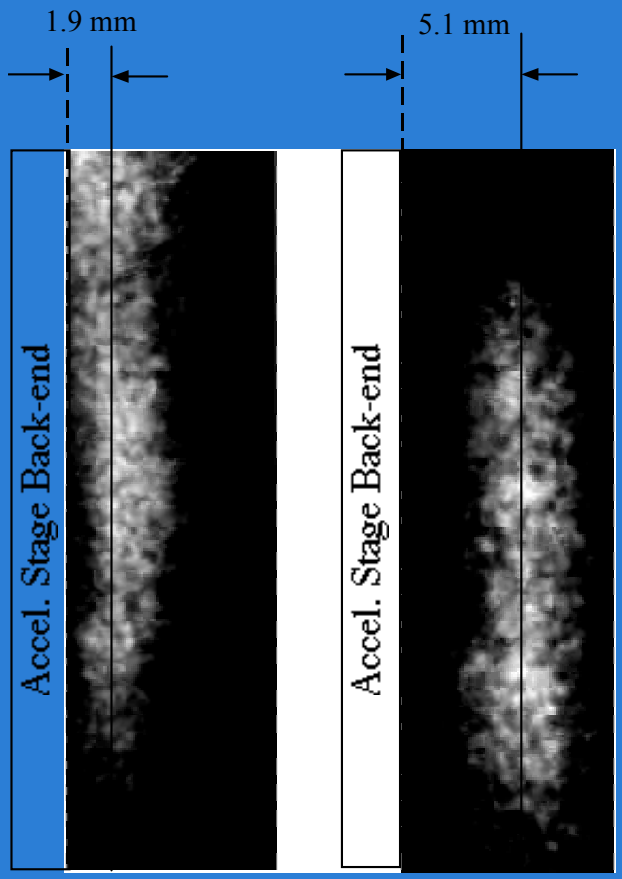

Magnet Casing
Set #1
#2
#3
#4
#5
Coils
r [cm]
Large Glass Vessel
G-11 Midplate
Small Glass Vessel
Induction Coil Cover
z [cm]


Measured (B = +/-1%)
Magnetic Field
Magnetic Flux Tubes
Mag. Field [Gauss]
r [cm]
Numerical
z [cm]

FARAD: Proof-of-Concept Experiment:
Demonstration of passive plasma feeding

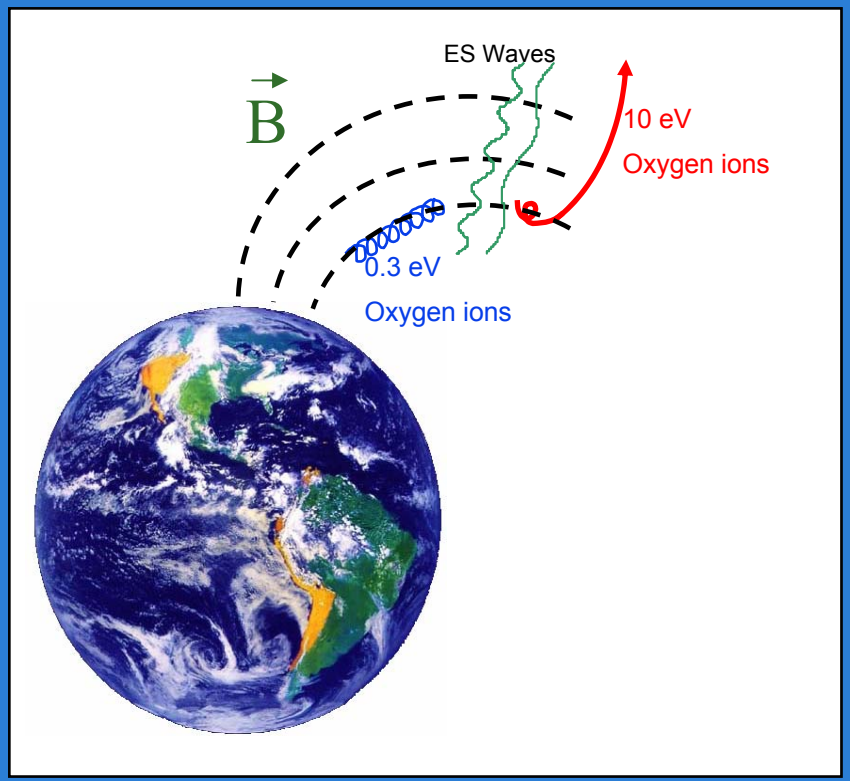


FARAD: Proof-of-Concept Experiment:
Demonstration of Current Sheet Formation and Acceleration



II. Ion Acceleration by Beating Electrostatic Waves

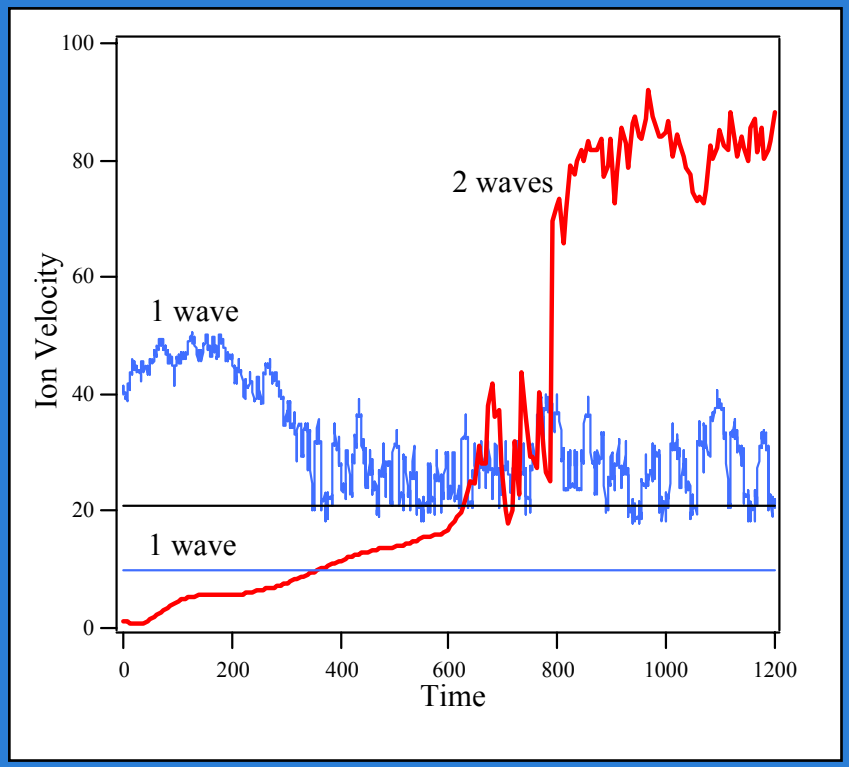
Inspiration : Ionospheric Observations



- Low-energy Ionospheric oxygen ions naturally accelerated and reach escape velocities.
- Intense Lower Hybrid Waves: ~ 100 mV/m, 2-12 kHz, Electrostatic in nature.
- Classical ion acceleration by (resonant) ES waves fails to explain the observations. (Initial ion velocity < Threshold interaction velocity)
- 1998: Benisti et. al. (MIT) propose that a beating of 2 ES waves may be responsible.

J. Geophys. Res. **103** *9431 (1998)*

Beating Waves Vs. Single Wave

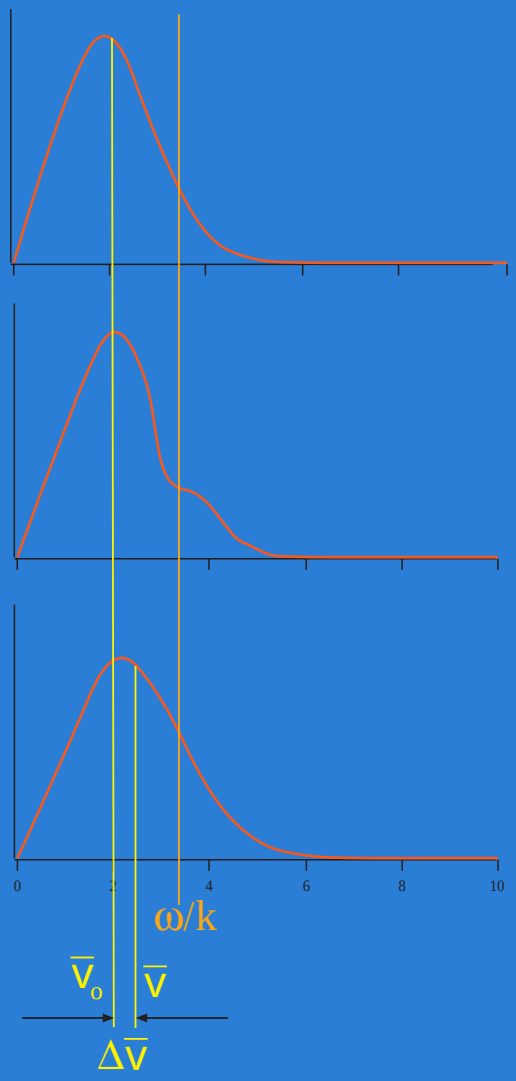


What are the conditions for Ion acceleration by Beating waves?

Necessary Condition: $\omega_i - \omega_j = n\omega_c$

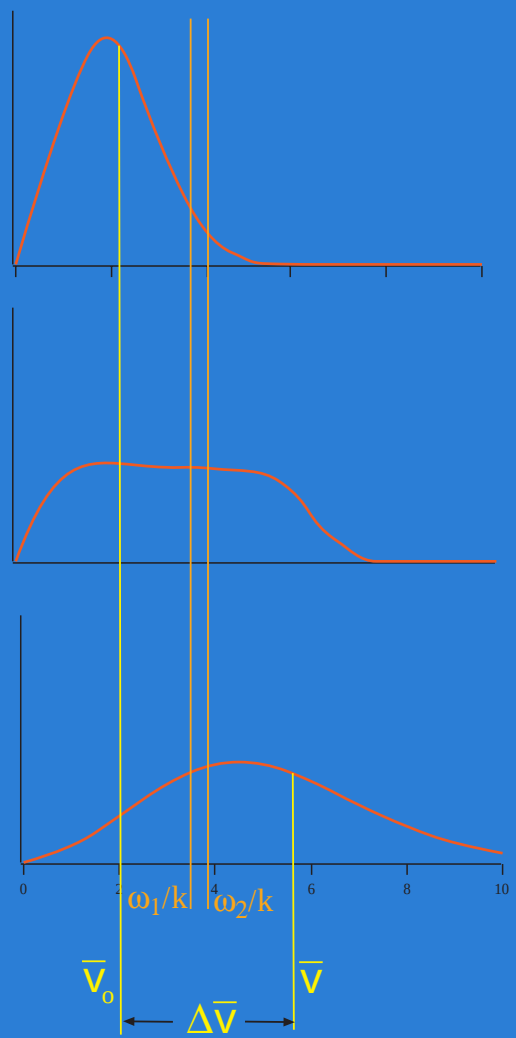
Resonant Energization

$\omega=\omega_{ci}$



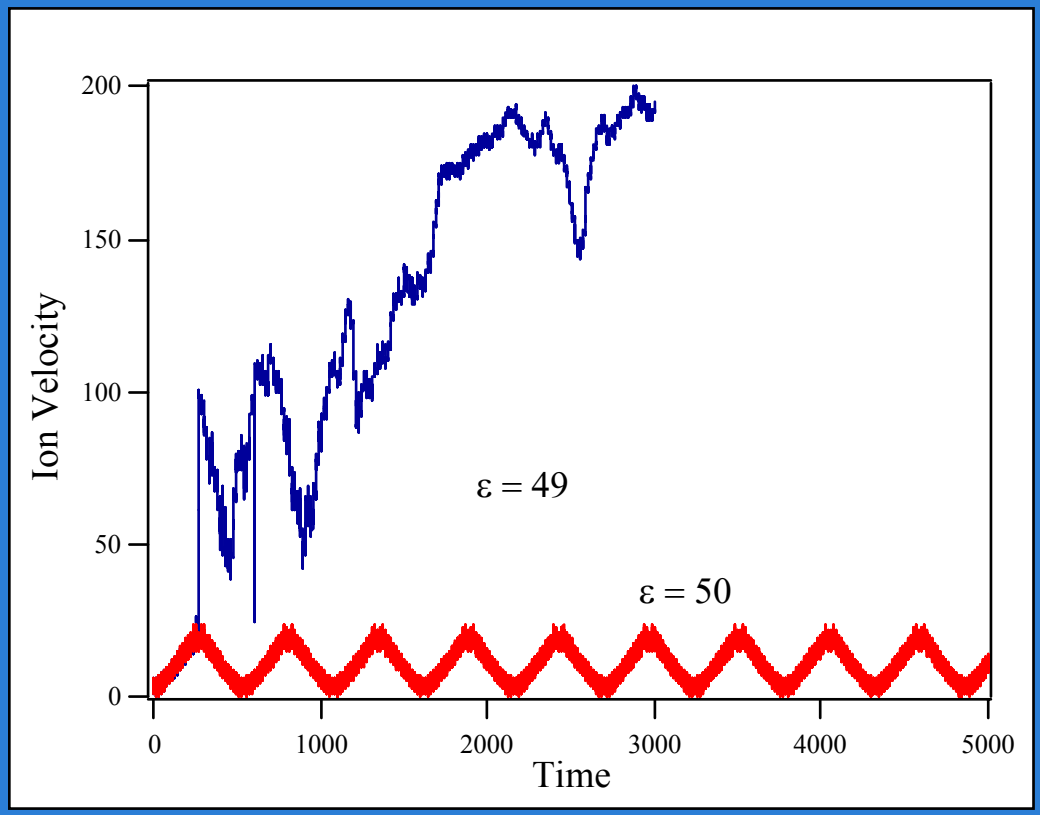
Beating Wave Energization

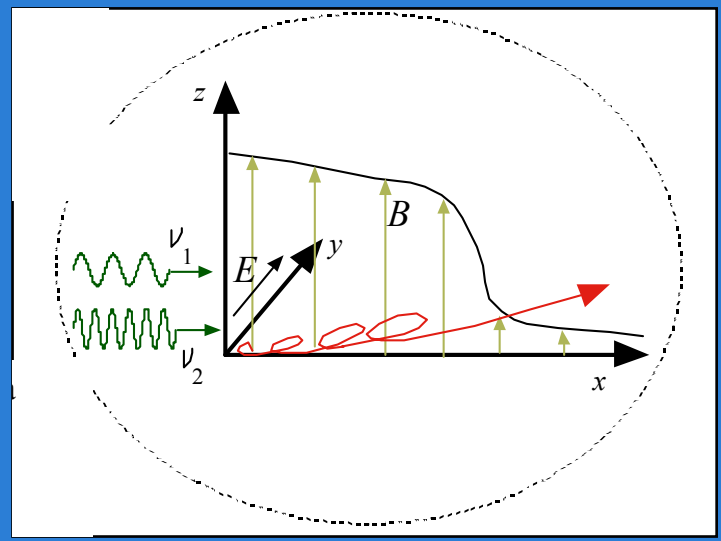
$\omega_2-\omega_1=\omega_{ci}$



Benisti's Criterion is not Sufficient!

Choueiri & Spektor, AIAA-2000-3759, IEPC-01-209





What are the necessary and sufficient conditions for Ion acceleration by beating waves?

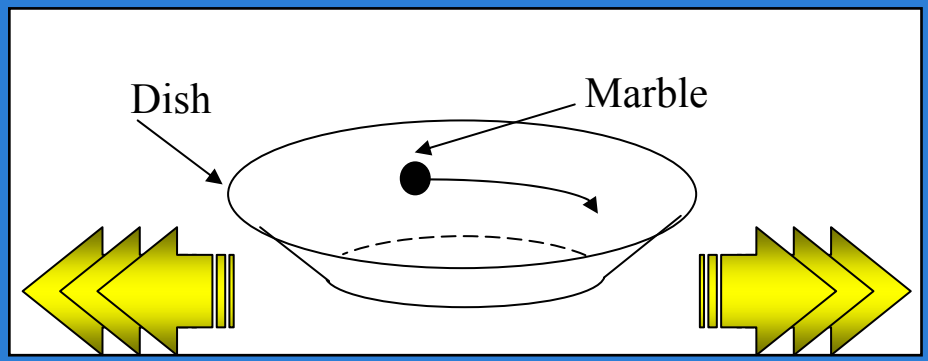
Are there Necessary and Sufficient Criteria for Acceleration?

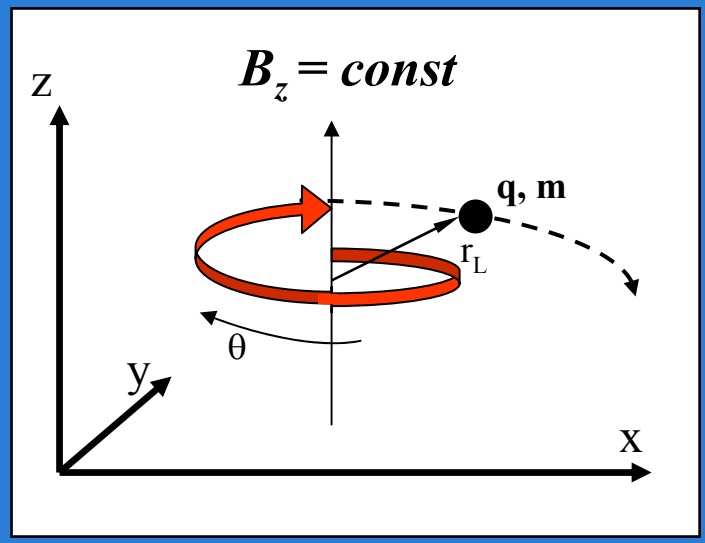
Yes

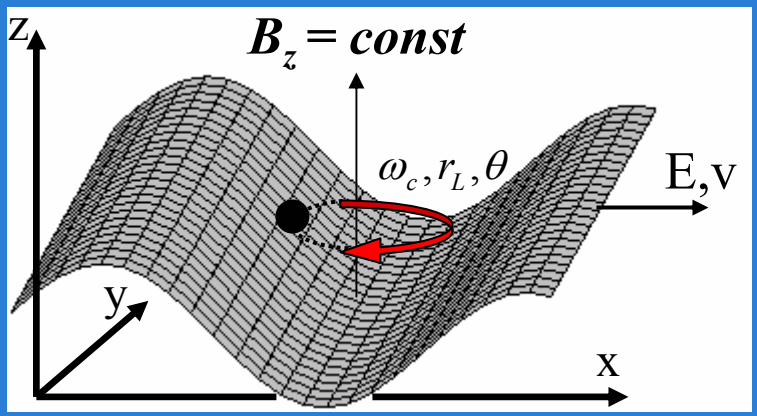
Spektor & Choueiri, *Physical Review E*, March 2004

Model – Basic Concept

Single particle, constant magnetic field, multiple waves







$$\ddot{x} + \omega_{ci}^2 x = \frac{q}{m} \sum_i E_i \cos(\kappa_i x - \omega_i t)$$

Approach

Hamiltonian

$$H = \frac{\rho^2}{2} + \sum_i \frac{\varepsilon_i}{\kappa_i} \cos(\kappa_i \rho \sin\theta - \nu_i \tau)$$

Numerical Solution: Symplectic Integration Algorithm

J. Comp. Phys. **92** *230 (1991)*

Analytical Solution: 2nd order perturbation theory + Lie transformations

Phys. Plasmas ***3****(5), May 1996, 1545*

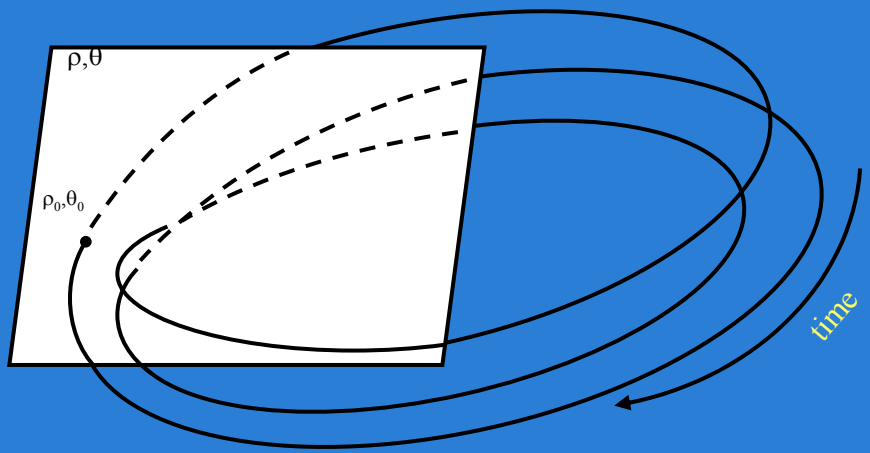
Poincare surface of section (Reduced phase space diagram)

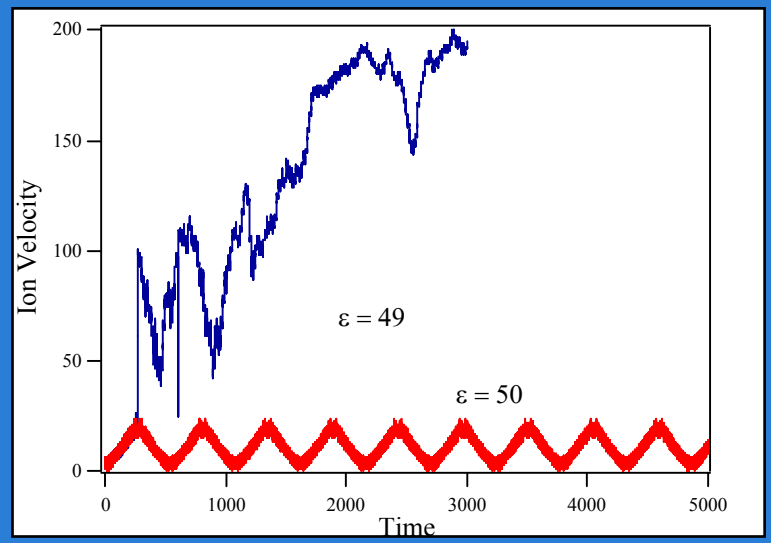
Poincare diagram construction

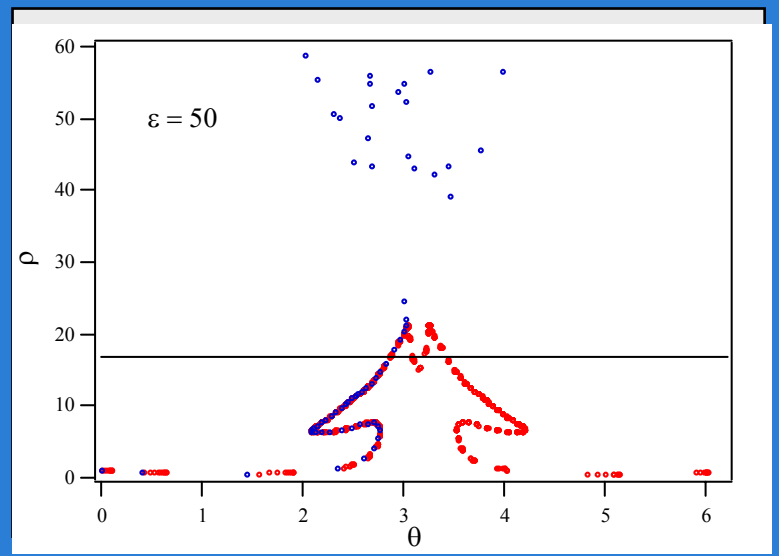
1 - D periodic Motion

$(\rho,\theta,t) = (\rho,\theta,t+T)$

T = period

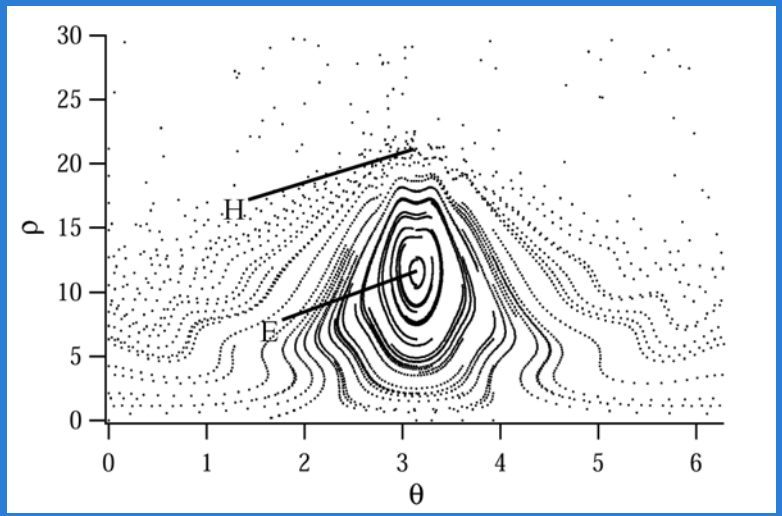




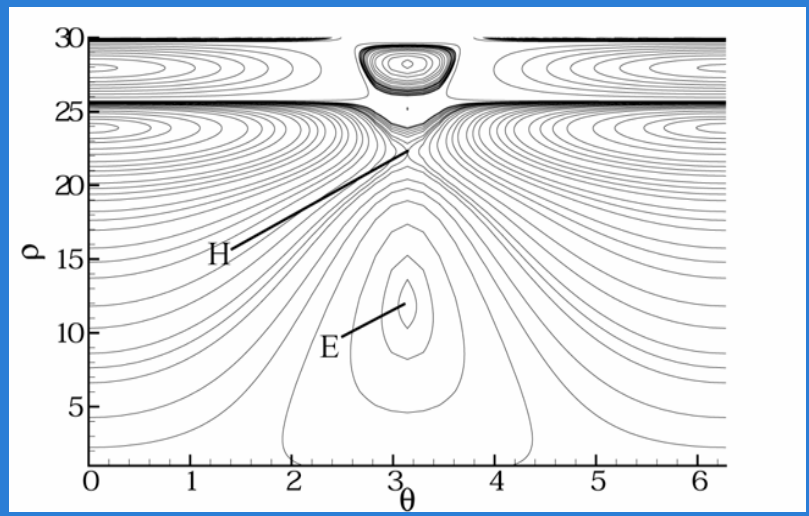


Trapped Particles & Domain of Allowed Acceleration

Numerical Simulation



2nd-order Perturbation Theory



Hamilton's Eqns

$$
\begin{aligned}
\dot{\rho} &= \frac{\partial H}{\partial \theta} = \varepsilon\{\nu_i J_{\nu_i}(\rho)\sin(\nu_i\theta) \\
&+ \nu_j J_{\nu_j}(\rho)\sin(\nu_j\theta)\} \\
&+ \varepsilon^2(\nu_i-\nu_j)S_6^{\nu_i,\nu_j}(\rho)\sin[(\nu_j-\nu_i)\theta] = 0, \\
\dot{\theta} &= -\frac{\partial H}{\partial \rho} = \varepsilon\{J'_{\nu_i}(\rho)\cos(\nu_j\theta) \\
&+ J'_{\nu_j}(\rho)\cos(\nu_j\theta)\} \\
&+ \varepsilon^2\{S_1^{'\nu_i}(\rho) + S_1^{'\nu_j}(\rho) \\
&+ S_6^{'\nu_i,\nu_j}(\rho)\cos[(\nu_i-\nu_j)\theta]\} = 0.
\end{aligned}
$$

$$
\begin{aligned}
H &= \frac{\varepsilon^2\pi}{8\sin\nu\pi}\left(1+\frac{\rho}{\nu}\cos\theta\right) \\
&\Big[- J_{\nu-1}(\rho)J_{-(\nu-1)}(\rho) + J_\nu(\rho)J_{-\nu}(\rho) \\
&+ J_{\nu+1}(\rho)J_{-(\nu+1)}(\rho) - J_{\nu+2}(\rho)J_{-(\nu+2)}(\rho)\Big]
\end{aligned}
$$

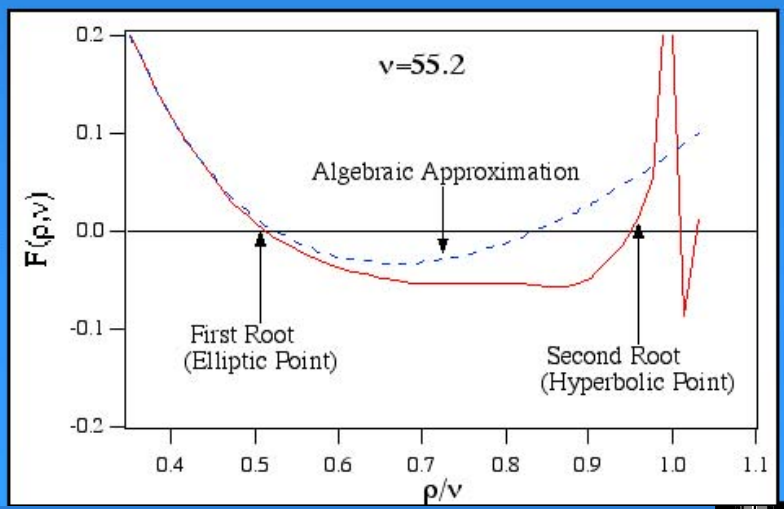
Hamiltonian from 2nd order perturbation theory + Lie Transforms

Bessel functions properties

$$
F(\rho,\nu) \simeq \frac{\rho}{\nu} - 1 + \frac{2}{3\left(f_{\nu-1} + f_{-(\nu-1)} + f_{\nu+2} + f_{-(\nu+2)}\right)} = 0
$$

where $f_\nu = f_\nu(\rho) \equiv J'_\nu / J_\nu$

Simplified Eqn. for locating critical points



Necessary and Sufficient Criteria

Benisti's beat criterion:

$$\omega_2 - \omega_1 = n\omega_c$$

Additional criterion:

$$H_H < H(\rho_0, \theta_0) < H_E$$

$$H_H = H(\rho \simeq \nu - \sqrt{\epsilon}; \theta = \pi).$$

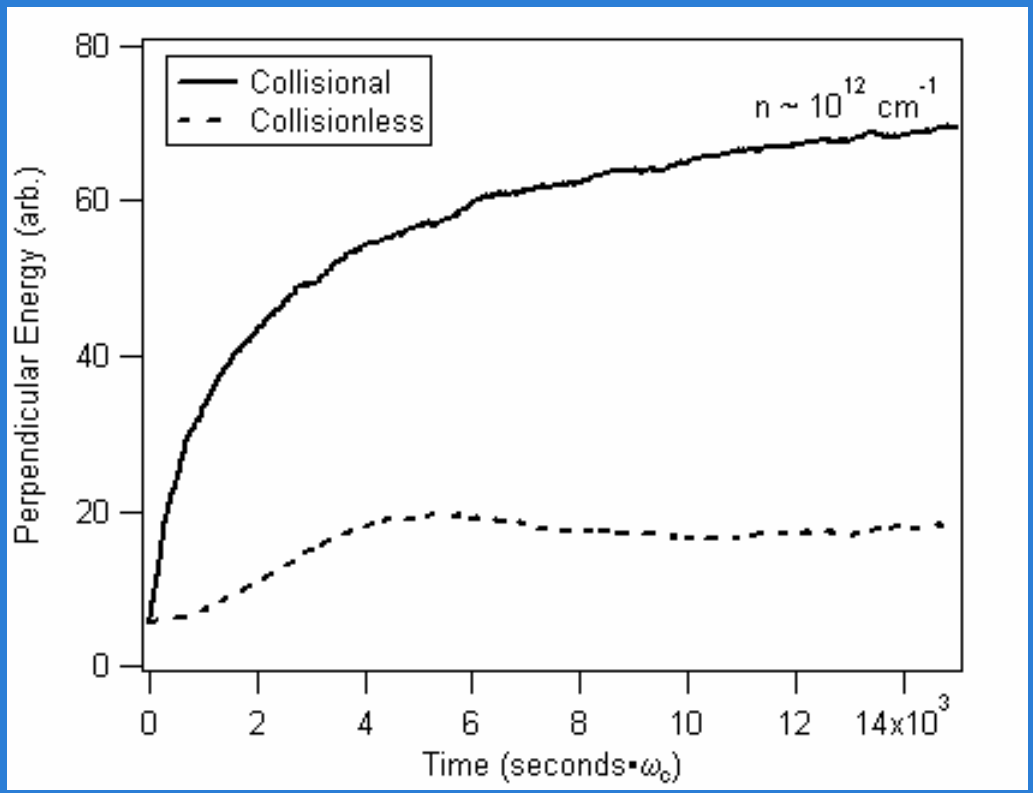
$$H_H \simeq H(v \simeq \frac{\omega}{k}; \theta = \pi).$$

$$H_E = H(\rho \simeq \frac{\nu - \sqrt{\epsilon}}{2}; \theta = \pi).$$

$$H_E \simeq H(v \simeq \frac{\omega}{2k}; \theta = \pi).$$

Does it work for many particles with collisions?

Monte Carlo simulations



$\nu_{ii} \sim 10 \bullet \omega_{ci}$

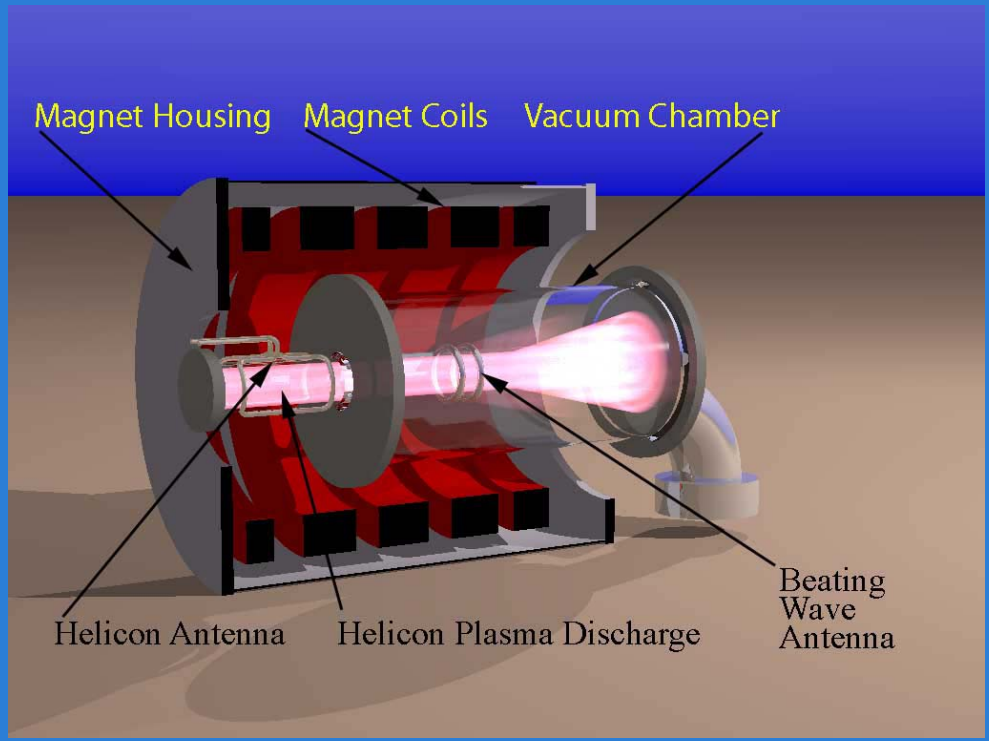
- Ion – ion collisions enhance acceleration!
- Ehancement is due to depopulation of trapped region of phase space due to collisions.

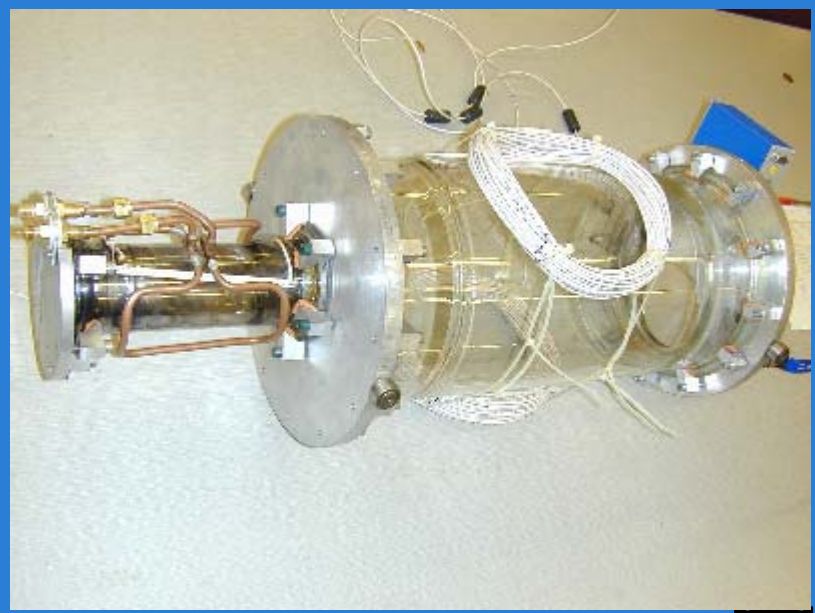
Summary of Theoretical Findings

- Previously proposed criterion is necessary but not sufficient.
- Poincare diagram shows that trapped particles lie between critical elliptic and hyperbolic points.
- New criterion found and relies on the value of the Hamiltonian at the motion's critical points.
- Collisions enhance the effect.
- Ions with arbitrarily low initial velocity can be accelerated in contrast with non-beating waves.
  - — Seems to occur naturally in the ionosphere
  - —Promise for propulsion applications and more efficient ion heating.

TIME FOR EXPERIMENTAL VERIFICATION

Experimental Apparatus





RF Power: 100 – 1200 Watt

Magnetic Field: 0.08 Tesla

Plasma Density: $10^{10} – 10^{13}$ cm^{-3}

$T_e \sim 3\text{-}5$ eV, $T_i \sim 0.1\text{-}0.3$ eV

Experimental Apparatus

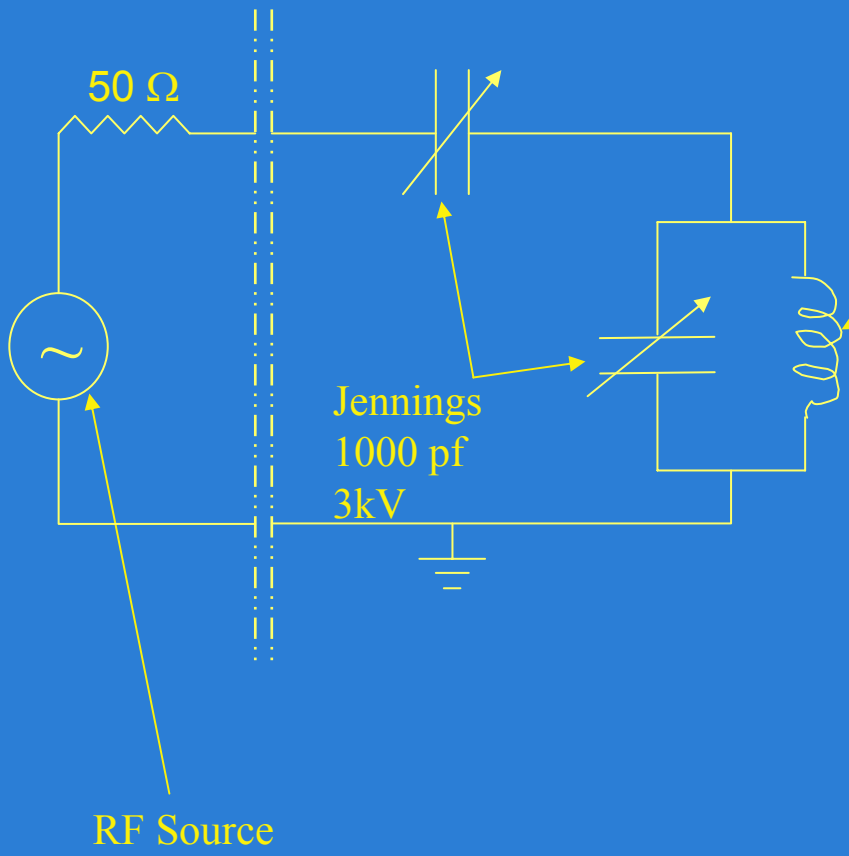
Base Pressure: ~ 10^{-6} Torr

Operating Pressure: ~ 10^{-3} Torr

Electric Circuit for Helicon Source

P_{RF} up to 1.2 kW

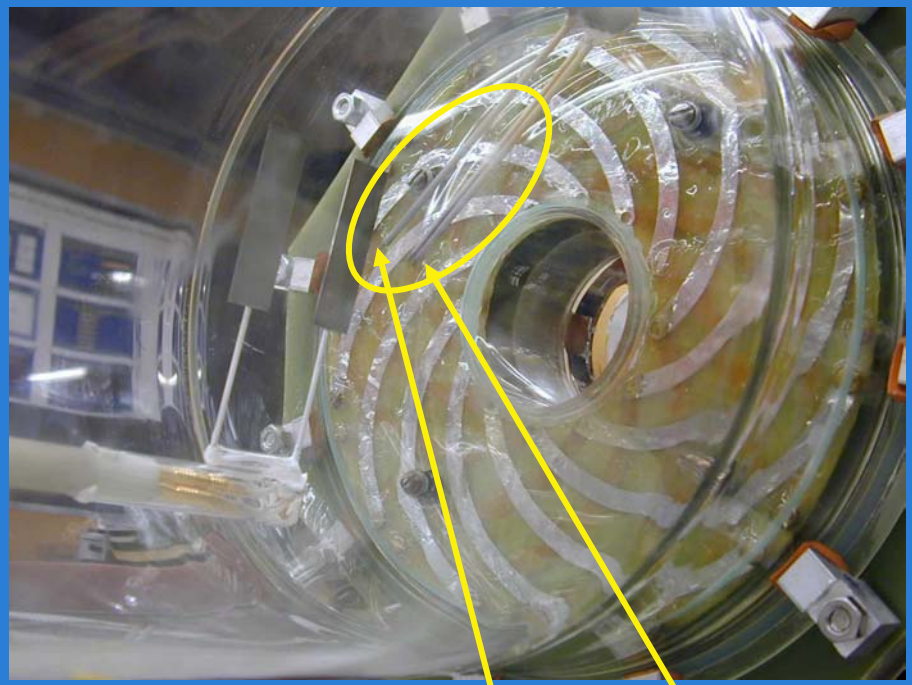
$\omega \sim 13.56$ MHz

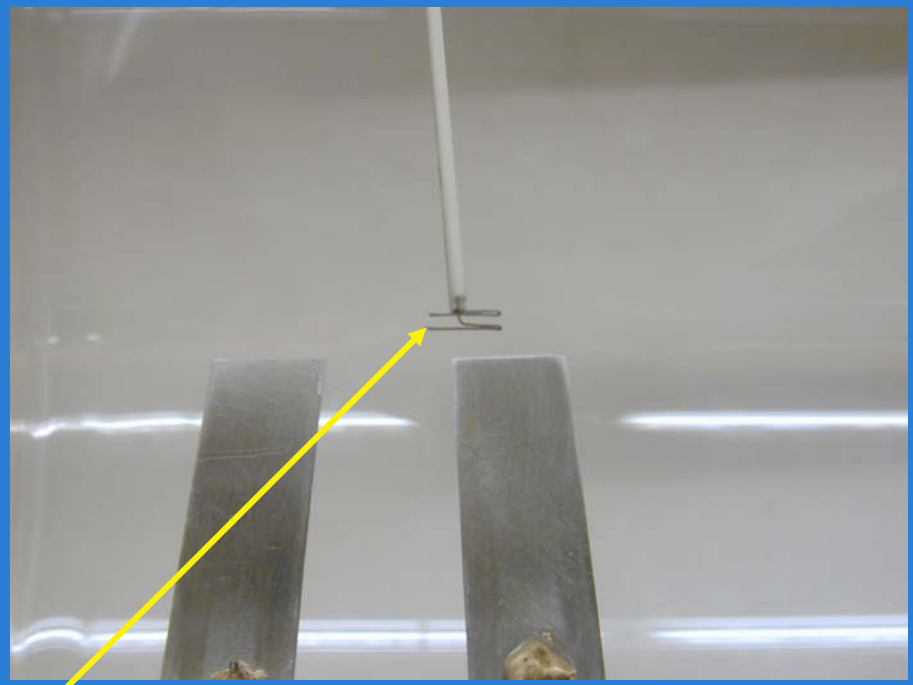


Dedicated Diagnostics

- Langmuir Probes (n_e, T_e)
- Hall Probes (B field)
- Probe interferometry (Dispersion Relation)
- Retarding Potential Analyzer (Ion velocity)
- LIF (Ion Velocity)

Launching Waves



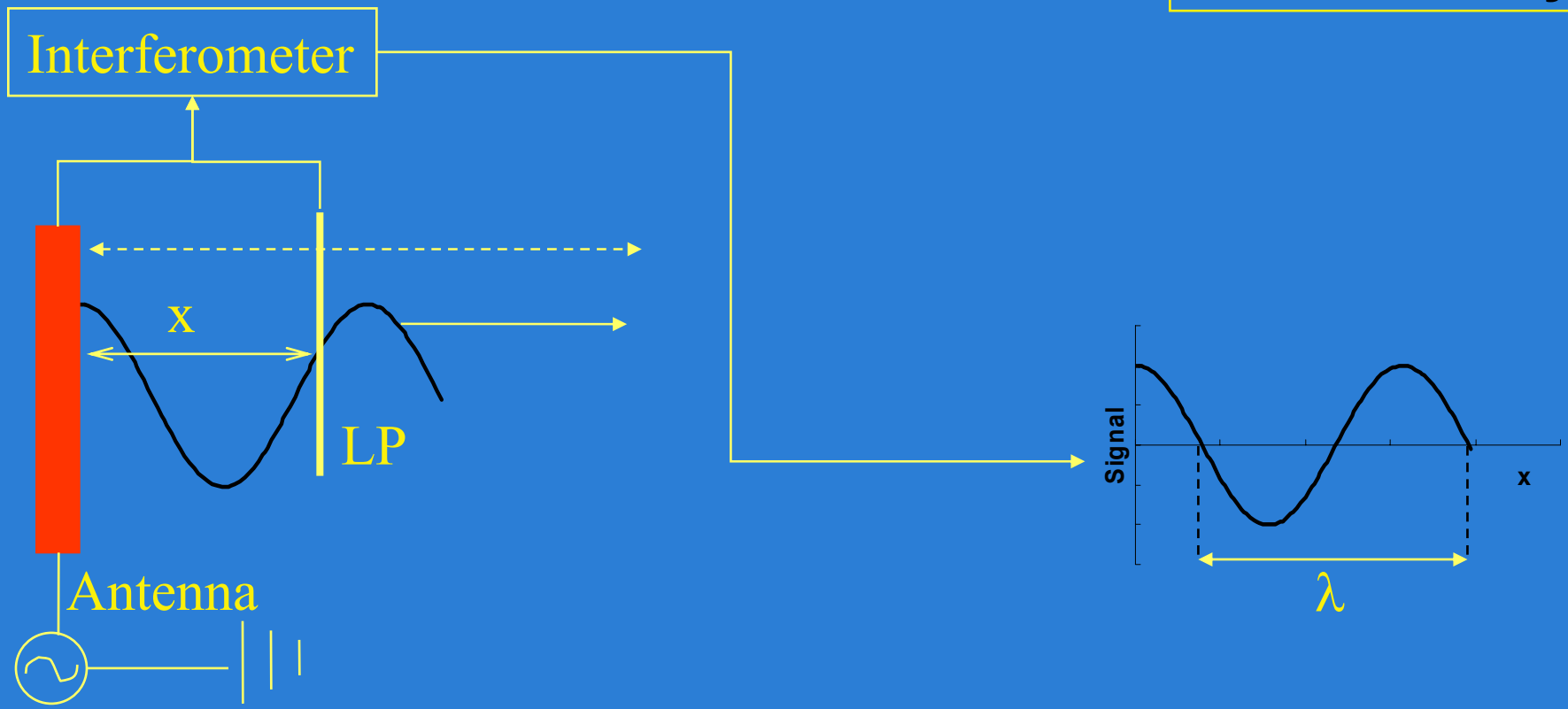


Langmuir Probes

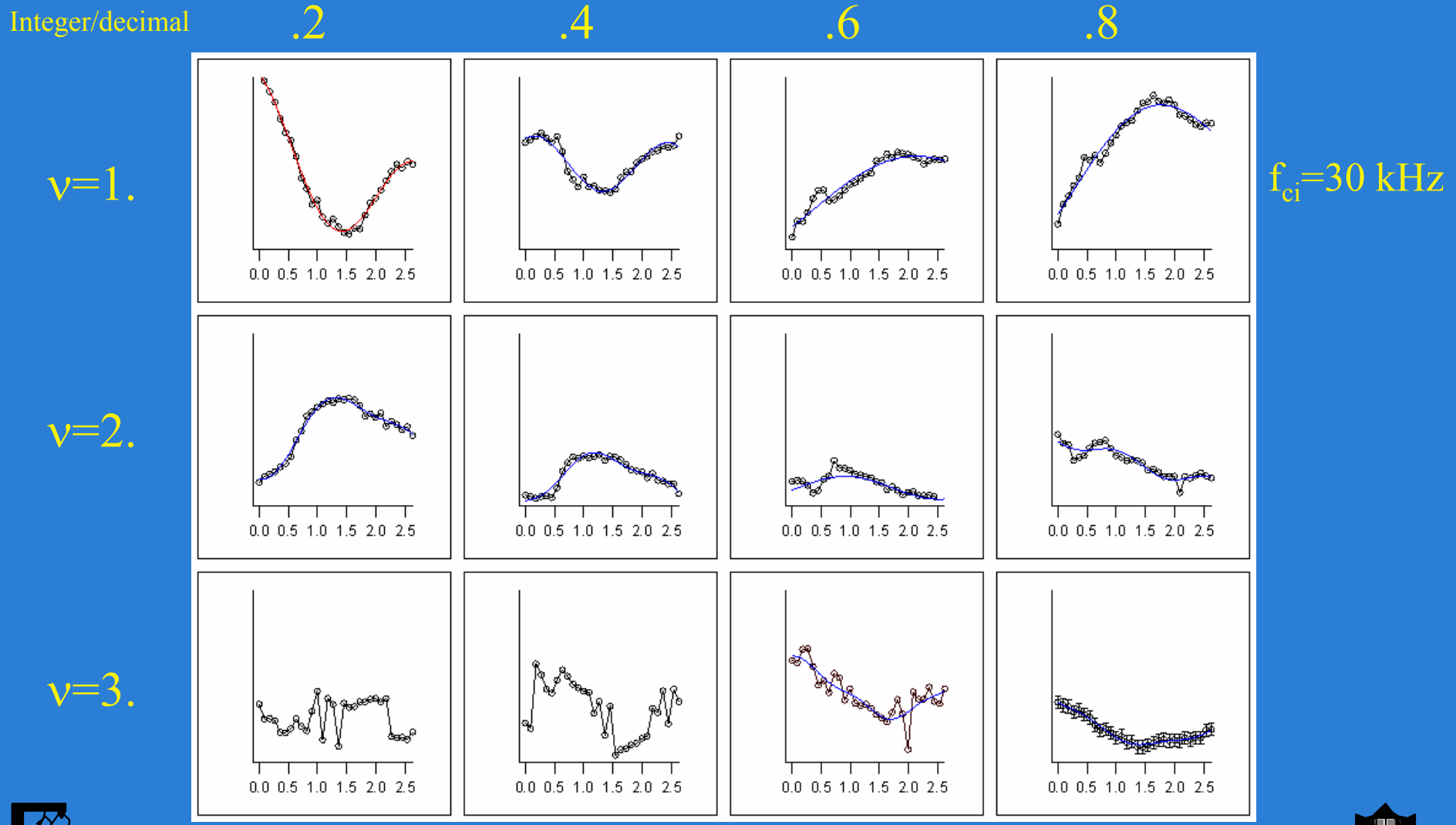
- Need to launch an electrostatic wave ⊥ to the magnetic field
- Measuring the dispersion to determine the nature of the wave

Detecting the Waves

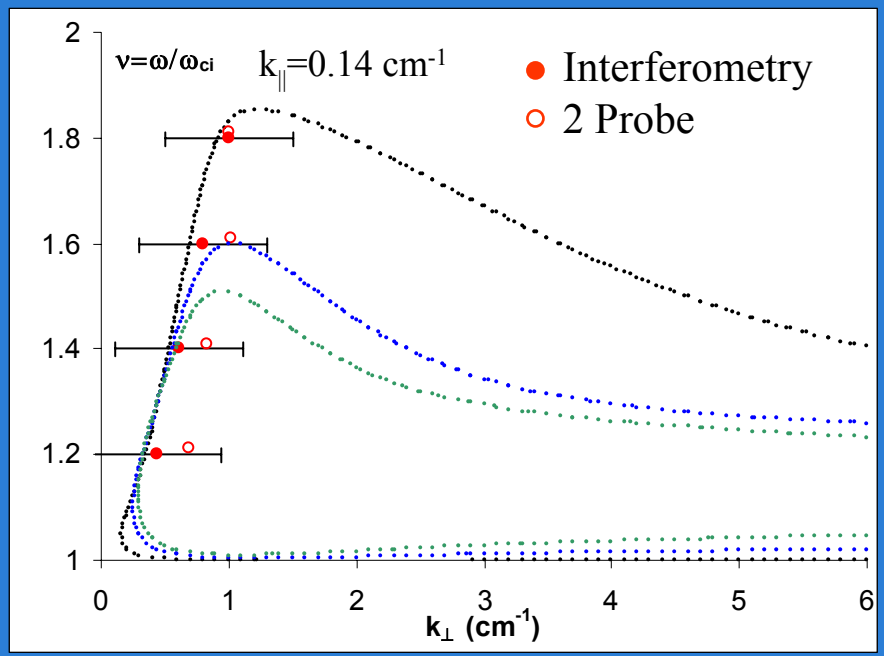
Interferometry



125 W Interferometry Data



Internal Antenna – Data Interpretation



- Electrostatic Ion Cyclotron fast wave is launched
- Good agreement with theory
- Indirect evidence of ion energization
- Direct evidence will be obtained next month with LIF

Conclusions

- Two electrodeless plasma acceleration concepts with promised for pulsed and steady-state propulsion are investigated

  - FARAD: Proof of concept experiment verified basic principle

  - Beating wave ion acceleration:

    - Found fundamental acceleration criteria
    - Monte Carlo simulation verified that the effect can exist in a real plasma with collisions
    - Dedicated experiment is yielding first laboratory observations of new acceleration mechanism.